Macromodelling and its Applications to Signal and Power Integrity

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S.Grivet-Talocia, “Macromodeling and its Applications for Signal and Power Integrity”, 8-Oct-2013, Intel, Munich

Outline

- Simulation of terminated interconnects
  - Frequency and time-domain analysis
- Transient analysis
  - Convolution-based approaches
  - Direct circuit simulation (when possible)
  - Black-box passive macromodeling
- Black-box passive macromodeling
  - Rational curve fitting
  - Passivity enforcement
  - Causality issues
- An application example
  - Coupled signal-power integrity analysis of a real board
- Current work and future developments
- Conclusions

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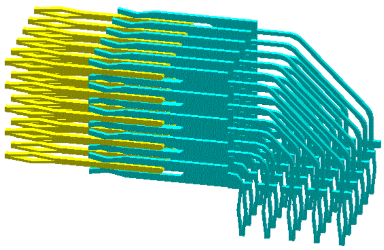
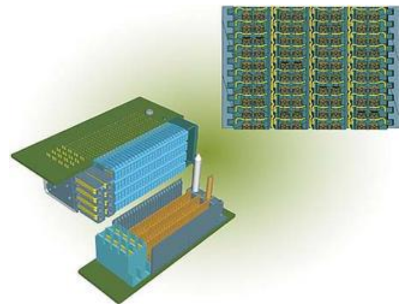
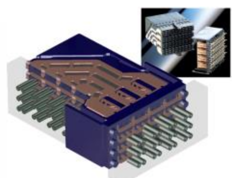
Interconnects: showcase







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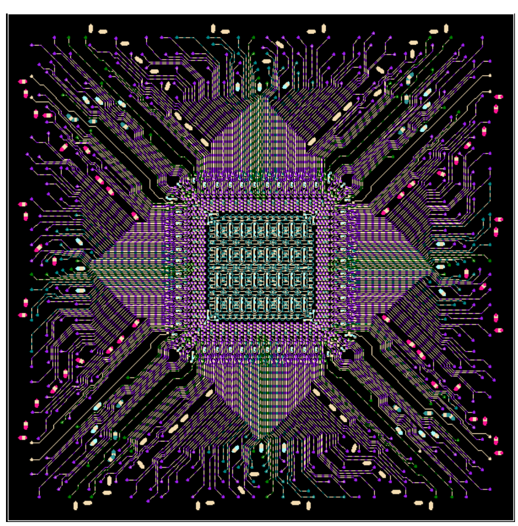
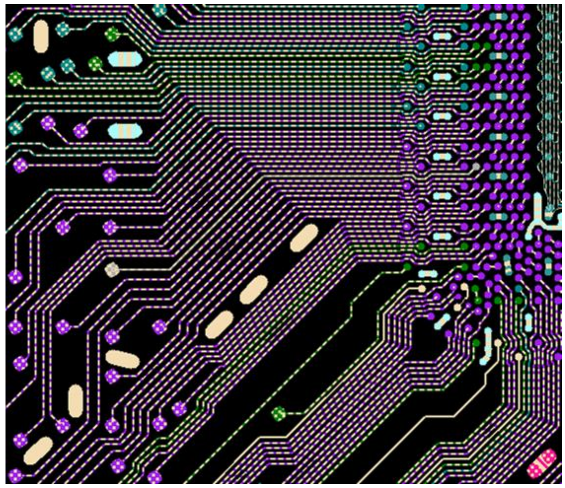


Interconnects: showcase



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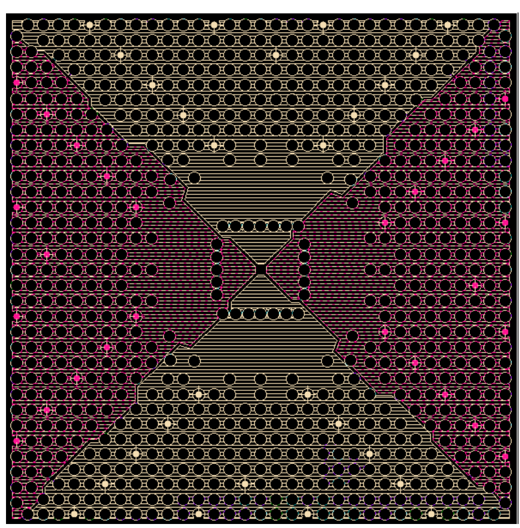
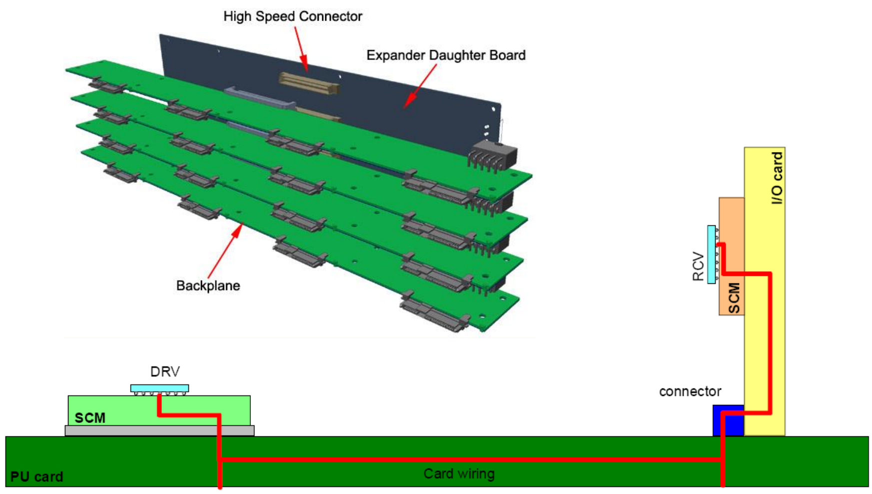
Interconnects: showcase

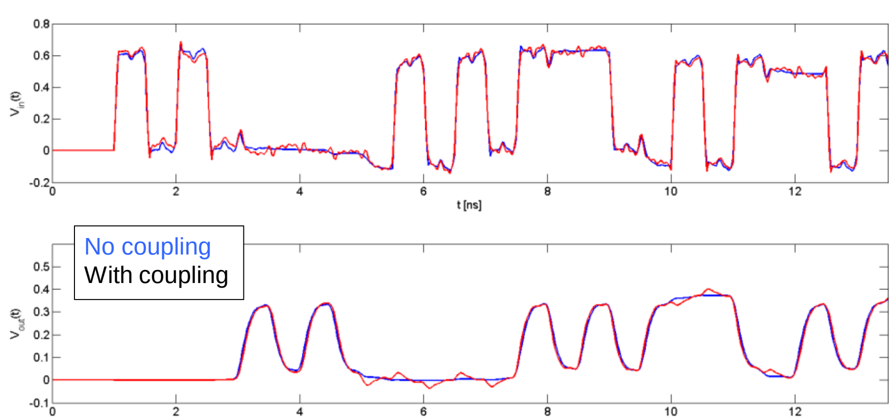


Interconnects: showcase



Courtesy D. Kaller, IBM Boeblingen, Germany

Signal Integrity



The objective

Terminations
Nonlinear
Complex

Interconnect network
Signal and Power
Linear
Many ports
Complex geometry
Electrically large

Terminations
Nonlinear
Complex

Terminations
Nonlinear
Complex

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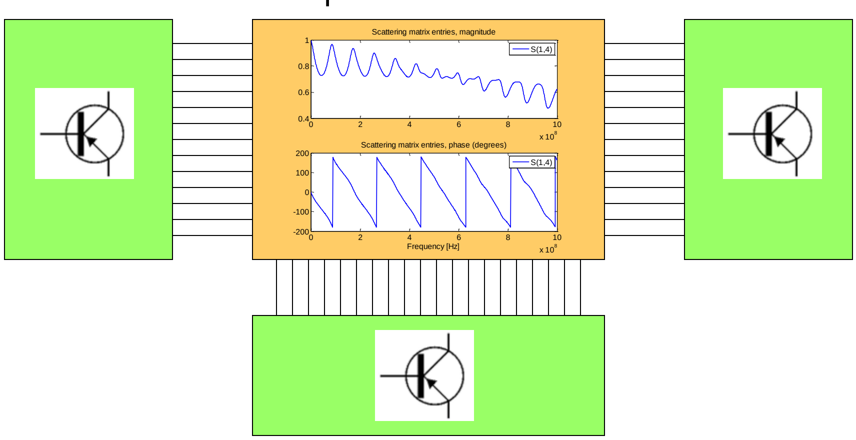
The objective

S-parameter block



Scattering variables

Voltage waves	Power waves	Current waves
$A = \frac{1}{2}\left(V + R_0 I\right)$	$A = \frac{1}{2\sqrt{R_0}}\left(V + R_0 I\right)$	$A = \frac{1}{2R_0}\left(V + R_0 I\right)$
$B = \frac{1}{2}\left(V - R_0 I\right)$	$B = \frac{1}{2\sqrt{R_0}}\left(V - R_0 I\right)$	$B = \frac{1}{2R_0}\left(V - R_0 I\right)$

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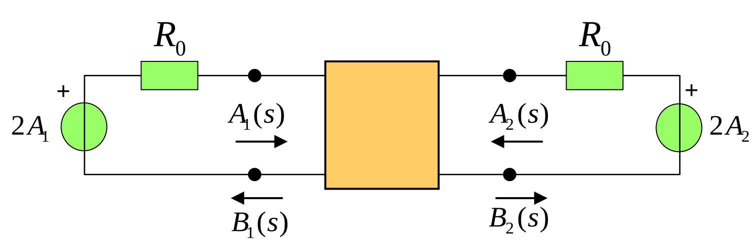
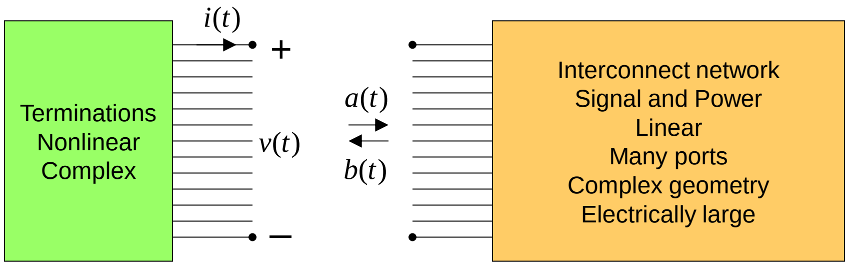
Scattering network functions



$$\begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = \underbrace{\begin{bmatrix} S_{11}(s) & S_{12}(s) \\ S_{21}(s) & S_{22}(s) \end{bmatrix}} \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}$$

Scattering matrix
main output of field solvers (at finite frequencies)

Connecting terminations



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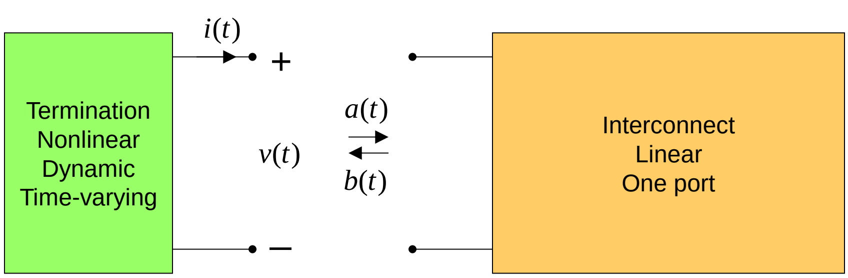
Nonlinear terminations



$$B(j\omega_k) = S(j\omega_k)\,A(j\omega_k)$$

$$f\left(v, i; \frac{d}{dt}; t\right) = 0$$

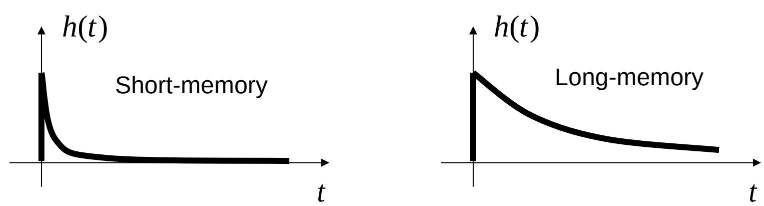
Inverse Fourier/Laplace transform

$$b(t) = h(t) * a(t) = \int_0^t h(t-\tau)\,a(\tau)\,d\tau$$

Discretizing convolution

$$b(t) = h(t) * a(t) = \int_0^t h(t-\tau)a(\tau)d\tau \qquad b(t_k) \approx \sum_{m=0}^{k-1} a(t_m)\Delta h_\Delta(t_k - t_m)$$

Memory: Number of non-vanishing time-samples in the impulse response



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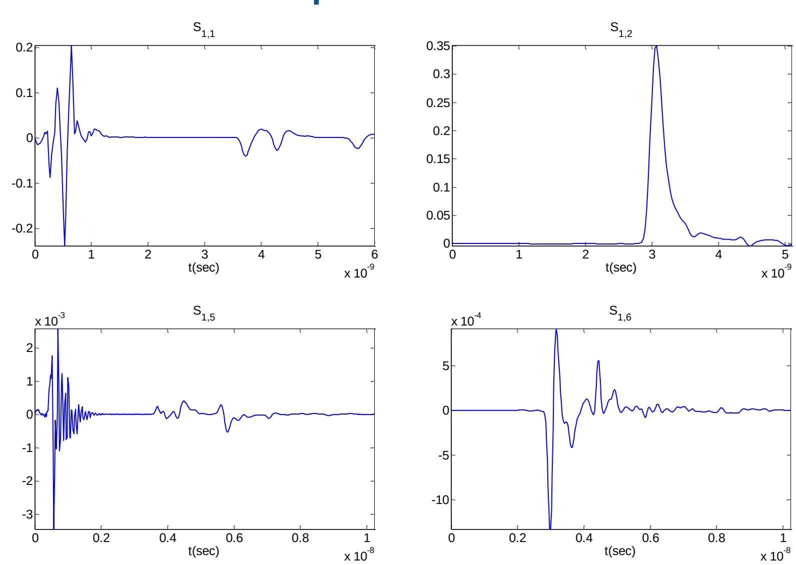
An example: CPU-I/O channel



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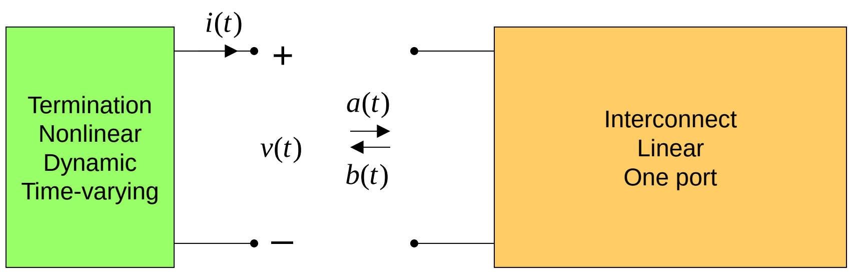
Direct convolution



$$f\left(v, i; \frac{d}{dt}; t\right) = 0$$

$$\left.\frac{dv}{dt}\right|_{t=t_k} \approx \frac{v(t_k) - v(t_{k-1})}{\Delta}$$

$$b(t_k) \approx \sum_{m=0}^{k-1} a(t_m) \Delta h_\Delta (t_k - t_m)$$

(e.g., backward Euler)

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Direct convolution

$$\boxed{F_k\big(v(t_k), i(t_k), v(t_{k-1}), i(t_{k-1})\big) = 0}$$

Need nonlinear solver

$$\boxed{b(t_k) \approx \sum_{m=0}^{k-1} a(t_m) \Delta h_\Delta (t_k - t_m)}$$

Use many past samples

$$a(t_k) = \frac{1}{2}\left(Z_R^{-1/2} v(t_k) + Z_R^{1/2}\, i(t_k)\right)$$

$$b(t_k) = \frac{1}{2}\left(Z_R^{-1/2} v(t_k) - Z_R^{1/2}\, i(t_k)\right)$$

May be very slow due to long memory in convolution

Very robust (when a good impulse response is available…)

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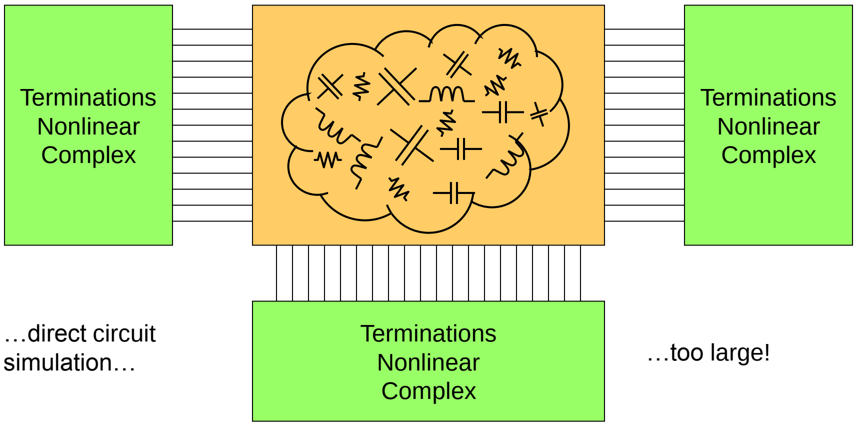
Direct circuit simulation

If a circuit description of the interconnect is available…



…direct circuit simulation…

…too large!

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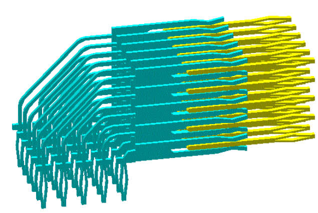
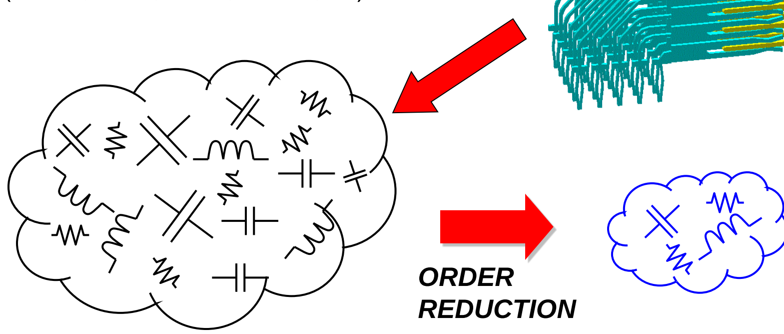
Model Order Reduction

Spatial discretization of Maxwell equations (FDTD, FEM, MoM, PEEC, …)





$$\mathbf{S}(s) \approx \mathbf{S}_q(s)$$

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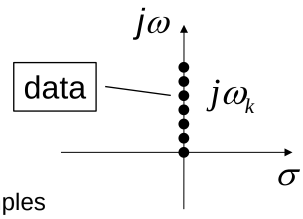
Black-Box Macromodeling

$$\mathbf{h}(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \mathbf{S}(j\omega)e^{j\omega t}d\omega$$



Parametric closed-form model fitting frequency samples

$$\mathbf{S}(s) \approx \sum_{n=1}^{N} \frac{\mathbf{R}_n}{s - p_n} + \mathbf{S}_\infty$$

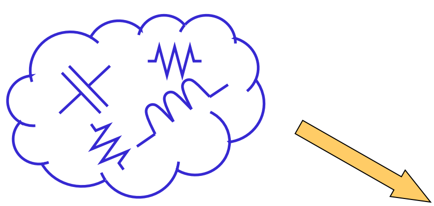
Macromodeling via rational function fitting $s = j\omega_k$

Analytic inversion of Laplace transform

$$\mathbf{h}(t) \approx \sum_{n=1}^{N} \mathbf{R}_n \exp(p_n t)u(t) + \mathbf{S}_\infty \delta(t)$$

May be used directly in SPICE via equivalent circuit extraction

Rational function fitting: why?



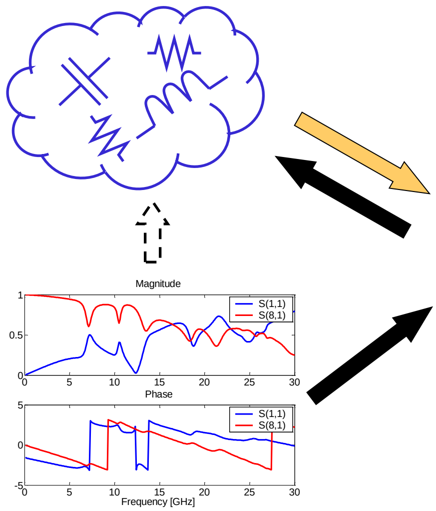
Circuit solvers understand circuits

Any lumped circuit has rational frequency responses (poles-residues, poles-zeros, ratio of polynomials)

$$\mathbf{S}(s) \approx \sum_{n=1}^{N} \frac{\mathbf{R}_n}{s - p_n} + \mathbf{S}_\infty$$

Impedance, admittance, scattering

Rational function fitting: why?



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$$\mathbf{S}(s) \approx \sum_{n=1}^{N} \frac{\mathbf{R}_n}{s - p_n} + \mathbf{S}_\infty$$

Impedance, admittance, scattering

Extraction of an equivalent circuit is an inverse problem (two-step)

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State-space realizations

$$\mathbf{S}(s) \approx \sum_{n=1}^{N} \frac{\mathbf{R}_n}{s - p_n} + \mathbf{S}_\infty$$

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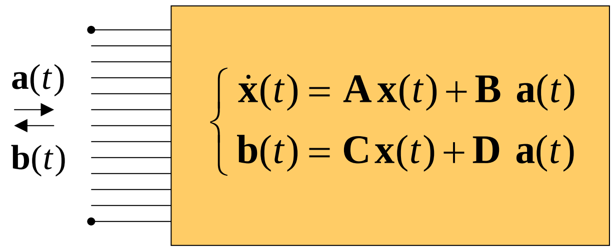
State-space realizations



$$\begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A}\,\mathbf{x}(t) + \mathbf{B}\;\mathbf{a}(t) \\ \mathbf{b}(t) = \mathbf{C}\,\mathbf{x}(t) + \mathbf{D}\;\mathbf{a}(t) \end{cases}$$

$$\mathbf{S}(s) \approx \sum_{n=1}^{N} \frac{\mathbf{R}_n}{s - p_n} + \mathbf{S}_\infty = \mathbf{D} + \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}$$

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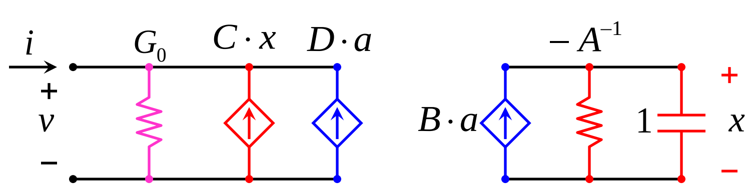
SPICE synthesis

Scattering representation

One-port, one-pole

$$\begin{cases} \dot{x} = A\,x + B\,a \\ b = C\,x + D\,a \end{cases}$$

$$a = G_0 v + i,\; b = G_0 v - i$$



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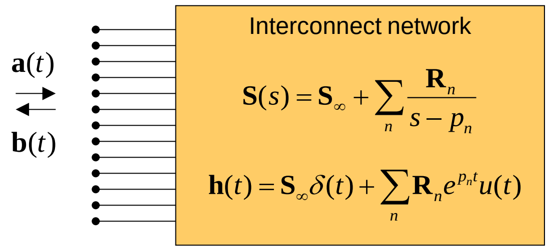
Recursive convolution



$$\mathbf{b}(t) = \mathbf{S}_\infty \mathbf{a}(t) + \sum_n \mathbf{R}_n \int_0^t e^{p_n(t-\tau)} \mathbf{a}(\tau) \mathrm{d}\tau = \mathbf{S}_\infty \mathbf{a}(t) + \sum_n \mathbf{R}_n \tilde{\mathbf{b}}_n(t)$$

Requires only one sample in the past!

$$\tilde{\mathbf{b}}(t_k) \approx e^{p\Delta} \tilde{\mathbf{b}}(t_{k-1}) + \frac{1 - e^{p\Delta}}{p} \mathbf{a}(t_k)$$

$$t_k = t_{k-1} + \Delta$$

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Macromodel implementations

1. Synthesize an equivalent circuit in SPICE format
   - No access to SPICE kernel
   - Must use standard circuit elements
2. Direct SPICE implementation via recursive convolution
   - Laplace element, most efficient
3. Other languages for mixed-signal analyses
   - Verilog-AMS, VHDL-AMS, …
   - Equation-based

Example: board with 13 ports →

	CPU time
Standard convolution	389 seconds
Equivalent circuit	180 seconds
Recursive convolution	5.8 seconds

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Rational curve fitting

Model: $S(s)$

3 alternative rational forms

$$\left\{ \begin{array}{l} S(s) = \dfrac{\alpha_0 + \alpha_1 s + \alpha_2 s^2 + \cdots + \alpha_N s^N}{\beta_0 + \beta_1 s + \beta_2 s^2 + \cdots + \beta_N s^N} \\ S(s) = \displaystyle\sum_{n=1}^{N} \frac{R_n}{s - p_n} + S_\infty \\ S(s) = S_\infty \dfrac{(s - z_1)(s - z_2)\cdots(s - z_N)}{(s - p_1)(s - p_2)\cdots(s - p_N)} \end{array} \right.$$

Fitting: $S(j\omega_k) \approx \hat{S}(j\omega_k) = \hat{S}_k \quad k = 1, \cdots, K$ Input data

Vector Fitting

$$\hat{S}(s) \approx S(s) = \frac{r_0 + \displaystyle\sum_{n=1}^{N} \frac{r_n}{s - q_n}}{c_0 + \displaystyle\sum_{n=1}^{N} \frac{c_n}{s - q_n}}$$

Input data

"starting poles" (arbitrary, as long as distinct)

Linearized (weighted) system: multiply by the denominator

$$\underbrace{\left[c_0 + \sum_{n=1}^{N} \frac{c_n}{s - q_n} \right]}\hat{S}(s) \approx r_0 + \sum_{n=1}^{N} \frac{r_n}{s - q_n} \qquad s = j\omega_k,\ k = 1, \ldots, K$$

The VF "weight function" $w(s) = c_0 + \displaystyle\sum_{n=1}^{N} \frac{c_n}{s - q_n}$

Linear Least Squares system!

Vector Fitting

$$w(s) = c_0 + \sum_{n=1}^{N} \frac{c_n}{s - q_n} = \frac{c_0 (s - q'_1)(s - q'_2)\cdots(s - q'_N)}{(s - q_1)(s - q_2)\cdots(s - q_N)}$$

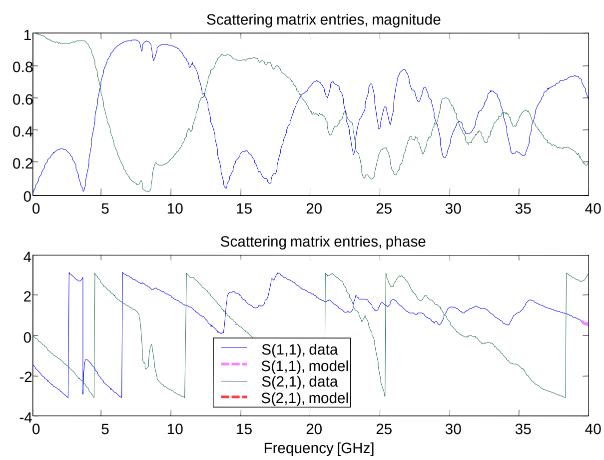
“Pole relocation” process

$$\{q_n\} \rightarrow \{q'_n\} \rightarrow \cdots \rightarrow \{p_n\}$$ “true poles”

At convergence: $w(s) \rightarrow \text{constant}$

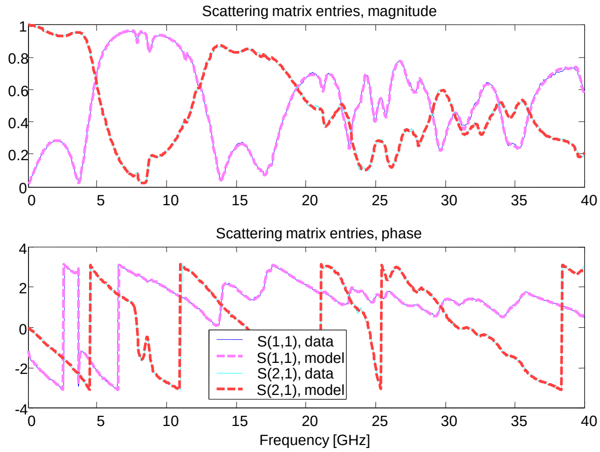
Stripline + launches

Data: measured S-parameters



Stripline + launches

Macromodel: 60 poles



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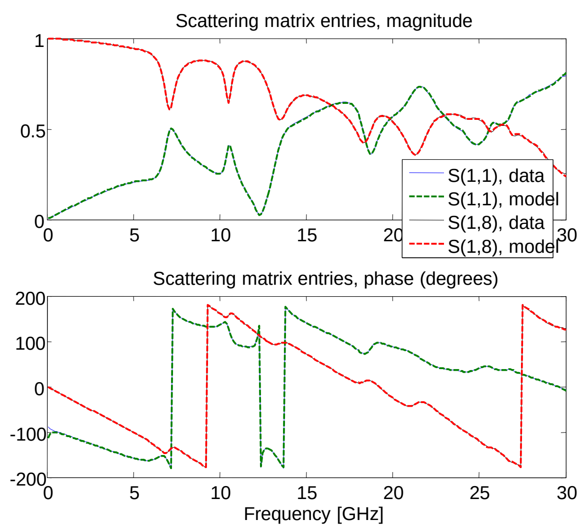
LGA via field (20 ports)



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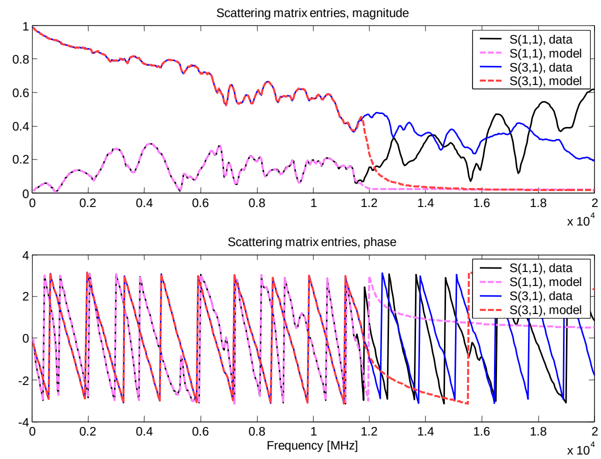
High-speed connector, measured



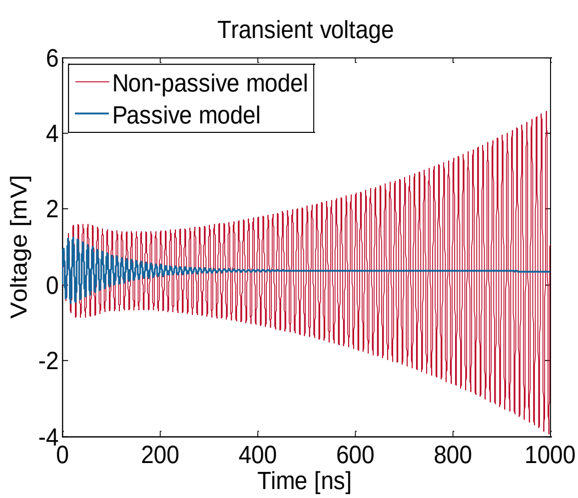
Advanced VF formulations

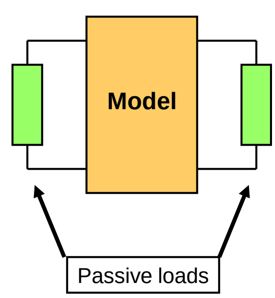
- Time-domain Vector Fitting
  - Processes time samples instead of frequency samples
- Orthonormal Vector Fitting
  - Further improvement in matrix conditioning using orthonormal rational functions
- Z-domain (orthonormal) Vector Fitting
  - Works on discrete-time/frequency systems
- Fast Vector Fitting
  - Uses smart QR decomposition (compressions) for systems with many ports
- Eigenvalue-based Vector Fitting
  - Possibly with relative error minimization, for improved robustness
- Multivariate/Parameterized Vector Fitting
  - Allows closed-form inclusion of geometry-material parameters in the macromodel equations
- Delayed Vector Fitting
  - Uses modified basis functions for representing propagation delays in closed form
- Parallel Vector Fitting
  - For multicore hardware architectures: close to ideal speedups, almost real-time modeling

Parallel VF for multicore platforms

Ports	Samples	Order	CPU Time 1 core	CPU Time 16 cores	Speedup
83	1228	30	196.08	14.36	13.7 X
48	690	26	28.32	2.10	13.5 X
56	1001	50	139.18	11.18	12.4 X
160	101	6	6.78	1.07	6.3 X
167	27	12	7.11	0.96	7.4 X
34	570	64	42.82	3.60	11.9 X

Passivity: why?





Passivity conditions (scattering)

1. $$\mathbf{S}(-j\omega) = \mathbf{S}^*(j\omega)$$

Guarantees real-valued impulse response.
Always assumed by construction

2. $$\left\|\mathbf{S}(j\omega)\right\| \leq 1 \quad \text{or} \quad \max_i \sigma_i\{\mathbf{S}(j\omega)\} \leq 1$$

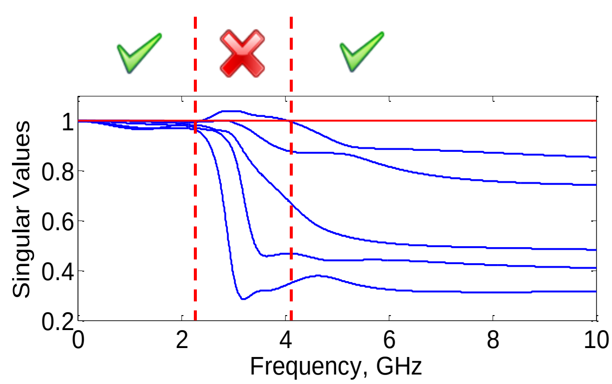
Energy condition: structure must not amplify signals.
Sometimes called simply “passivity” condition

3. $\mathbf{S}(j\omega)$ is causal

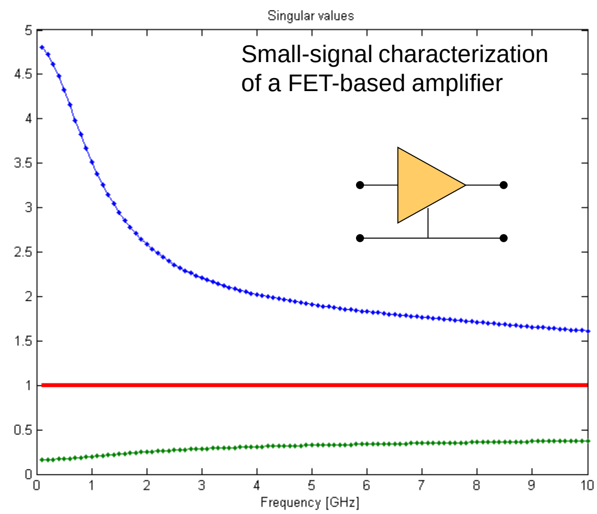
No anticipatory behavior in time-domain.
Note: causality is a prerequisite for passivity!
Guaranteed if macromodel is stable.

Passivity constraints (scattering)

$$\boxed{\mathbf{S}(s) \text{ is passive} \Leftrightarrow \{\text{singular values of } \mathbf{S}(j\omega)\} \leq \mathbf{1}, \forall\omega}$$



Not all S-parameter models should be passive



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Passivity violations: why?

- Data from measurement
  - Improper calibration and de-embedding, human mistakes
  - Measurement noise
- Data from simulation
  - Poor meshing
  - Inaccurate solver
  - Bad models or assumptions on material properties
  - Poor data post-processing algorithms
  - Putting together results from two solvers
- Macromodel
  - Approximation errors in Vector Fitting
  - May be critical out-of-band, where no data sample is available

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Checking passivity (scattering)

$$\boxed{\left\{\text{singular values of } \mathbf{S}(j\omega)\right\} \le \mathbf{1}, \quad \forall\omega}$$

Several techniques can be used

Frequency sweep test: most straightforward

- Choose a set of frequency samples
- Compute ***S*** and its singular values, and check
- Time-consuming for large models
- May give wrong answers due to poor sampling

Checking passivity

$$\boxed{\left\{\text{singular values of } \mathbf{S}(j\omega)\right\} \le \mathbf{1}, \quad \forall\omega}$$

State-space macromodel

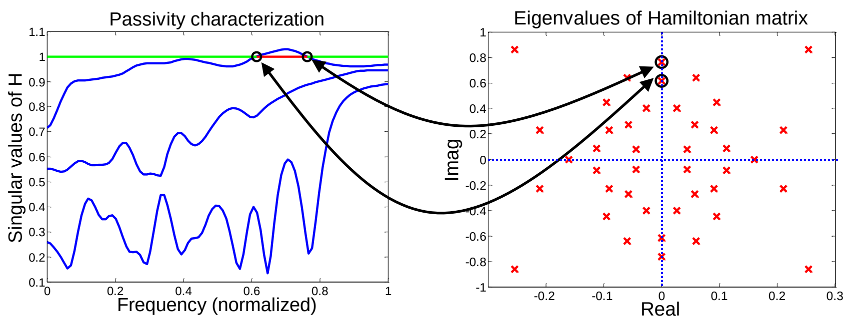
$$\begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A}\,\mathbf{x}(t) + \mathbf{B}\;\mathbf{a}(t) \\ \mathbf{b}(t) = \mathbf{C}\,\mathbf{x}(t) + \mathbf{D}\;\mathbf{a}(t) \end{cases}$$

Eigenvalues of Hamiltonian matrix

$$\mathbf{M} = \begin{pmatrix} \mathbf{A} - \mathbf{B}\left(\mathbf{D}^T\mathbf{D} - \mathbf{I}\right)^{-1}\mathbf{D}^T\mathbf{C} & -\mathbf{B}\left(\mathbf{D}^T\mathbf{D} - \mathbf{I}\right)^{-1}\mathbf{B}^T \\ \mathbf{C}^T\left(\mathbf{D}\mathbf{D}^T - \mathbf{I}\right)^{-1}\mathbf{C} & -\mathbf{A}^T + \mathbf{C}^T\mathbf{D}\left(\mathbf{D}^T\mathbf{D} - \mathbf{I}\right)^{-1}\mathbf{B}^T \end{pmatrix}$$

Real matrix $\mathbf{M}$ must have no imaginary eigenvalues

Checking passivity



Theorem

$$j\omega_0 \text{ is an eigenvalue of } \mathbf{M} \Leftrightarrow \sigma = 1 \text{ is a singular value of } \mathbf{S}(j\omega_0)$$

S.Grivet-Talocia, “Macromodeling and its Applications for Signal and Power Integrity”, 8-Oct-2013, Intel, Munich

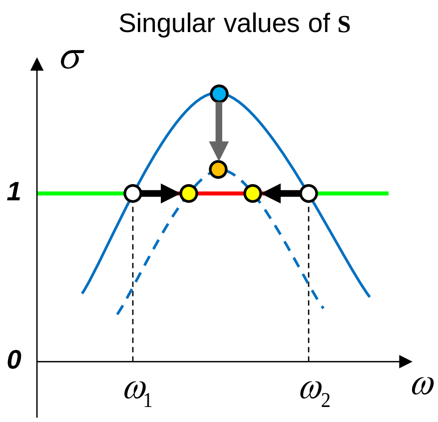
Passivity enforcement

- Generate a new passive macromodel
- Apply small correction to preserve accuracy
  - original dataset should be passive
  - original macromodel should be accurate
  - (usually) preserve poles

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\,\mathbf{a} \\ \mathbf{b} = \mathbf{C}\mathbf{x} + \mathbf{D}\,\mathbf{a} \end{cases} \Longrightarrow \begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\,\mathbf{a} \\ \mathbf{b} = (\mathbf{C} + \Delta\mathbf{C})\mathbf{x} + \mathbf{D}\,\mathbf{a} \end{cases}$$

$$\Delta\mathbf{S} = \Delta\mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}$$

Model Perturbation



$$\begin{cases} \min \| \mathbf{w} \|_2 \\ \mathbf{Q}\,\mathbf{w} = \mathbf{y} \\ \mathbf{R}\mathbf{w} \le \mathbf{b} \end{cases}$$

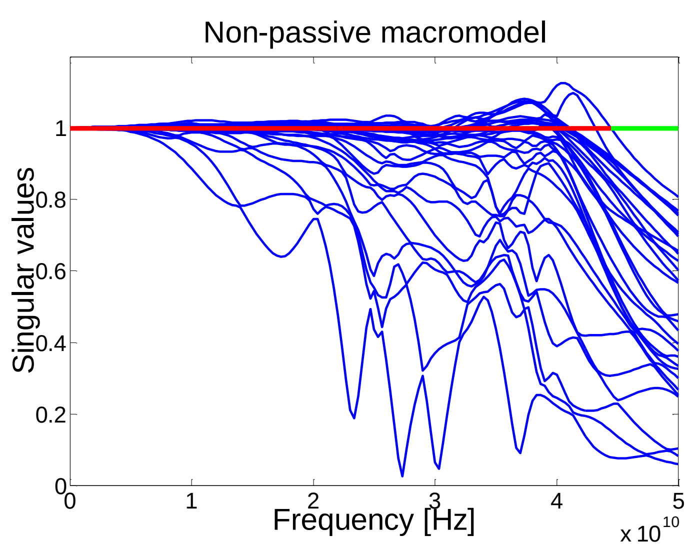
accuracy

passivity

- Few and simple constraints
- Convex: robust solution

S.Grivet-Talocia, “Macromodeling and its Applications for Signal and Power Integrity”, 8-Oct-2013, Intel, Munich

Example: 28-port package



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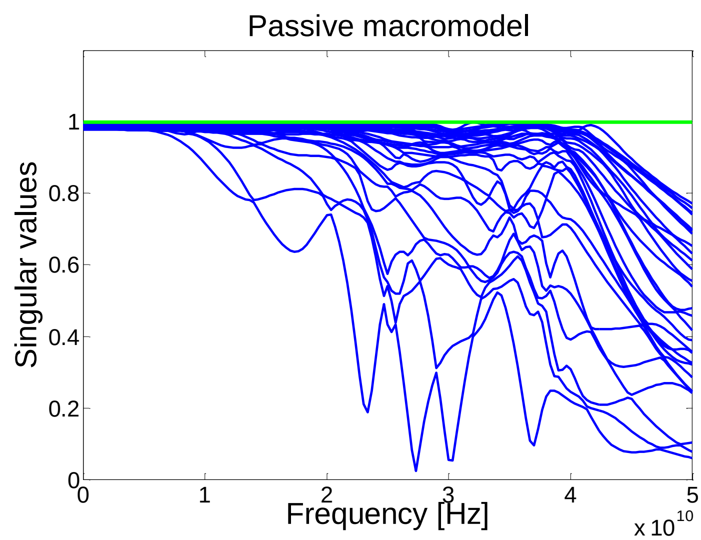
Example: 28-port package



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The GIGO rule

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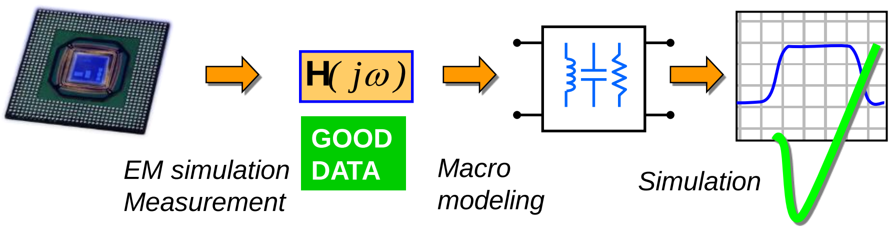
Data qualification

High-speed interconnects design via macromodels

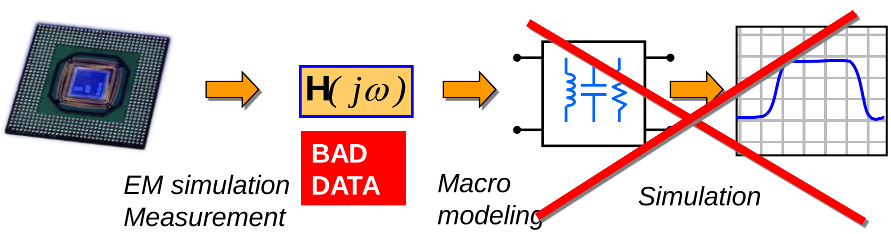


“Good” frequency data → **OK!**

S.Grivet-Talocia, “Macromodeling and its Applications for Signal and Power Integrity”, 8-Oct-2013, Intel, Munich

Data qualification

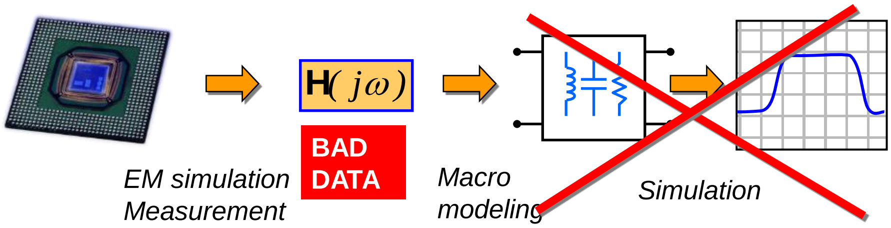
High-speed interconnects design via macromodels



“Bad” frequency data → **FAILURE**

Data qualification

High-speed interconnects design via macromodels

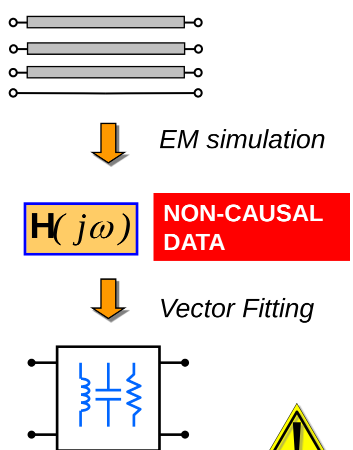


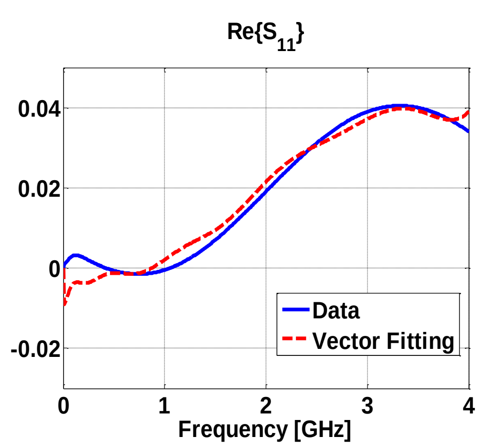
"Bad" frequency data → **FAILURE**

- passivity violations
- causality violations

Even macromodel generation may fail!

An example





Fitting dramatically fails!

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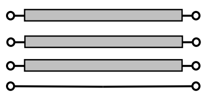
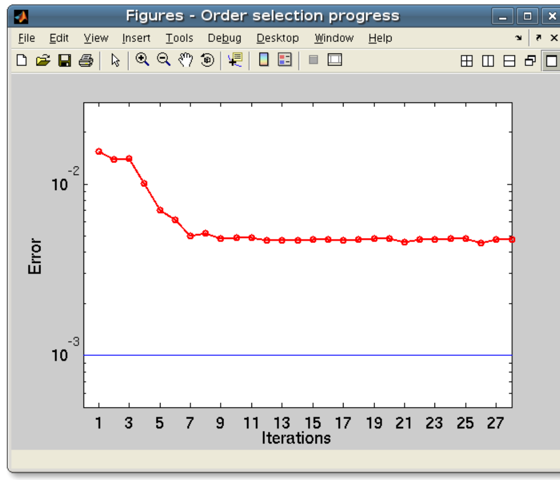
An example

Three coupled lines



Vector fitting fails... because of causality violations!

Even if the number of poles is increased up to 50, error does not decrease!



Courtesy of IdemWorks s.r.l.

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An example

Data from frequency domain simulation.

```
Building model New using FDVF
Performing FDVF Model Generation ...
Iteration 1
Warning: flipped real pole
Warning: flipped real pole
Warning: flipped real pole
Warning: flipped real pole
  RMS Error: 0.00498987    Max Dev: 0.0122055

.... [snip] ....

Iteration 15
Warning: flipped real pole
Warning: flipped real pole
Warning: flipped real pole
Warning: flipped real pole
  RMS Error: 0.00385667    Max Dev: 0.0100463
End of FDVF Model generation
```

Vector Fitting fails because of causality violations!

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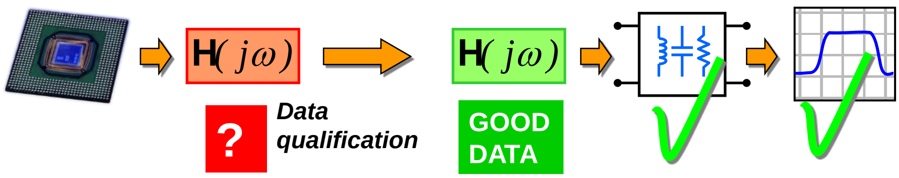
Data qualification

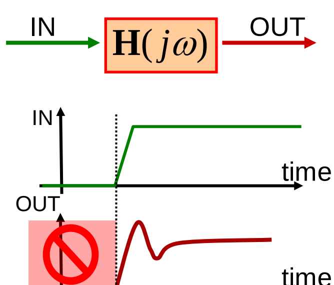
For successful macromodeling...



- **Passivity check on raw data**
- **Causality check on raw data**

Causality and dispersion relations

Time-domain



Any physical system cannot predict future!

Frequency-domain

Kramers-Krönig **dispersion relations**

Hilbert transform

$$H(j\omega) = U(\omega) + jV(\omega)$$

$$\begin{cases} U(\omega) = \dfrac{1}{\pi}\, pv \displaystyle\int_{-\infty}^{+\infty} V(\omega')\dfrac{d\omega'}{\omega-\omega'} \\ V(\omega) = -\dfrac{1}{\pi}\, pv \displaystyle\int_{-\infty}^{+\infty} U(\omega')\dfrac{d\omega'}{\omega-\omega'} \end{cases}$$

This check now available in EDA tools

A case study: coupled Signal/Power Integrity

This case study courtesy of

- Georgia Institute of Technology, Atlanta GA, USA
- E-System Design, Inc.
  - Provided field solver Sphinx
- Politecnico di Torino
- IdemWorks s.r.l.
  - Provided passive macromodeling tool IdEM

E-System Design www.e-systemdesign.com

IDEMWORKS www.idemworks.com

S.Grivet-Talocia, “Macromodeling and its Applications for Signal and Power Integrity”, 8-Oct-2013, Intel, Munich

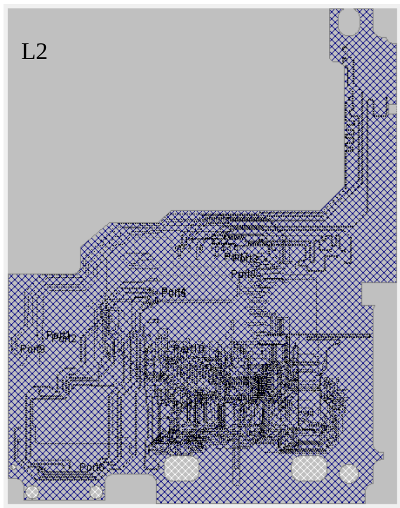
Board cross-section

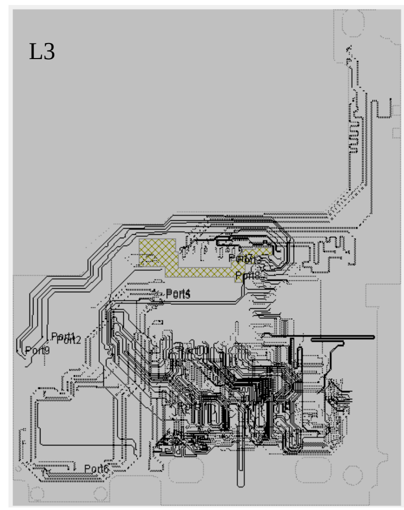
Layout Cross Section

Cross Section

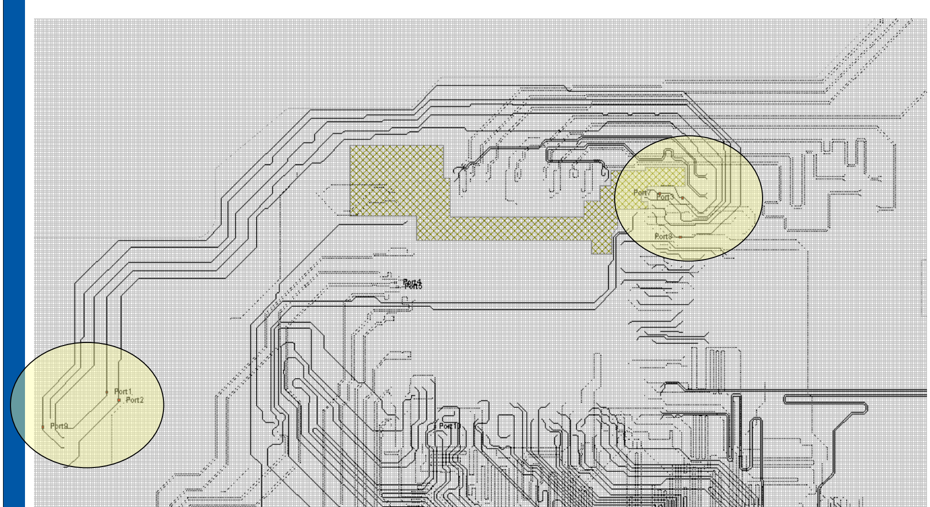
	Subclass Name	Type	Material	Thickness (MIL)	Conductivity (mho/cm)	Dielectric Constant	Loss Tangent	Negative Artwork	Shield	Width (MIL)
1		SURFACE	AIR			3.7	0			
2	TOP	CONDUCTOR	COPPER	1.25	595900	3.7	0	☐		5.000
3		DIELECTRIC	FR-4	2.8	0	3.7	0.035			
4	L2	PLANE	COPPER	0.7	595900	3.7	0	☐	☒	
5		DIELECTRIC	FR-4	2.8	0	3.7	0.035			
6	L3	CONDUCTOR	COPPER	0.7	595900	3.7	0	☐		5.000
7		DIELECTRIC	FR-4	6	0	3.7	0.035			
8	L4	CONDUCTOR	COPPER	0.7	595900	3.7	0	☐		5.000
9		DIELECTRIC	FR-4	3.6	0	3.7	0.035			
10	L5	PLANE	COPPER	1.2	595900	3.7	0	☐	☒	
11		DIELECTRIC	FR-4	3.5	0	3.7	0.035			
12	L6	PLANE	COPPER	1.2	595900	3.7	0	☐	☒	
13		DIELECTRIC	FR-4	2	0	3.7	0.035			
14	L6A	PLANE	COPPER	1.2	595900	4.5	0	☐	☒	
15		DIELECTRIC	FR-4	4	0	3.7	0.035			
16	L7A	PLANE	COPPER	1.2	595900	4.5	0	☐	☒	
17		DIELECTRIC	FR-4	2	0	3.7	0.035			
18	L7	PLANE	COPPER	1.2	595900	3.7	0	☐	☒	
19		DIELECTRIC	FR-4	3.5	0	3.7	0.035			
20	L8	PLANE	COPPER	1.2	595900	3.7	0	☐	☒	
21		DIELECTRIC	FR-4	3.6	0	3.7	0.035			
22	L9	CONDUCTOR	COPPER	0.7	595900	3.7	0	☐		5.000
23		DIELECTRIC	FR-4	6	0	3.7	0.035			
24	L10	CONDUCTOR	COPPER	0.7	595900	3.7	0	☐		5.000
25		DIELECTRIC	FR-4	2.8	0	3.7	0.035			
26	L11	PLANE	COPPER	0.7	595900	3.7	0	☐	☒	
27		DIELECTRIC	FR-4	2.8	0	3.7	0.035			
28	BOTTOM	CONDUCTOR	COPPER	1.25	595900	3.7	0	☐		5.000
29		SURFACE	AIR			3.7	0			

Layers L2 and L3

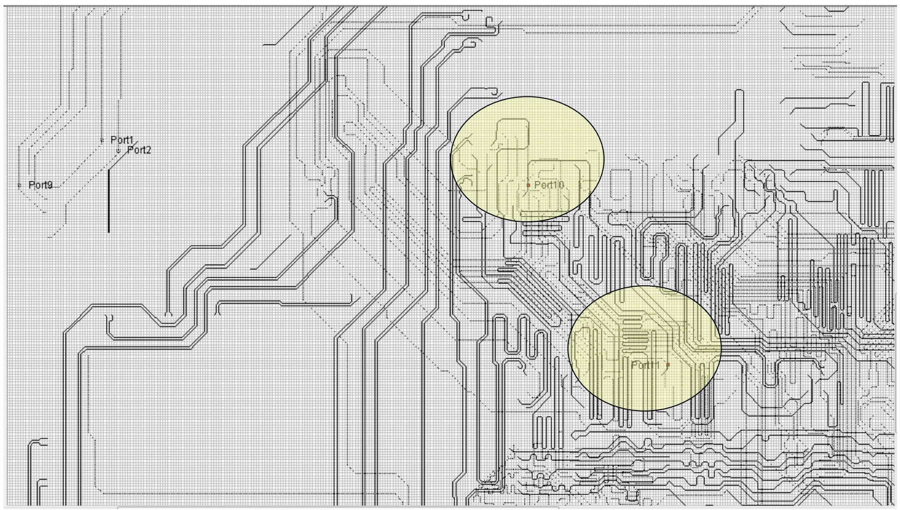




Port locations: L3 (Ref: L2) ports 1,7; 2,3; 8,9



Port locations: L4 (Ref: L5) ports 10,11



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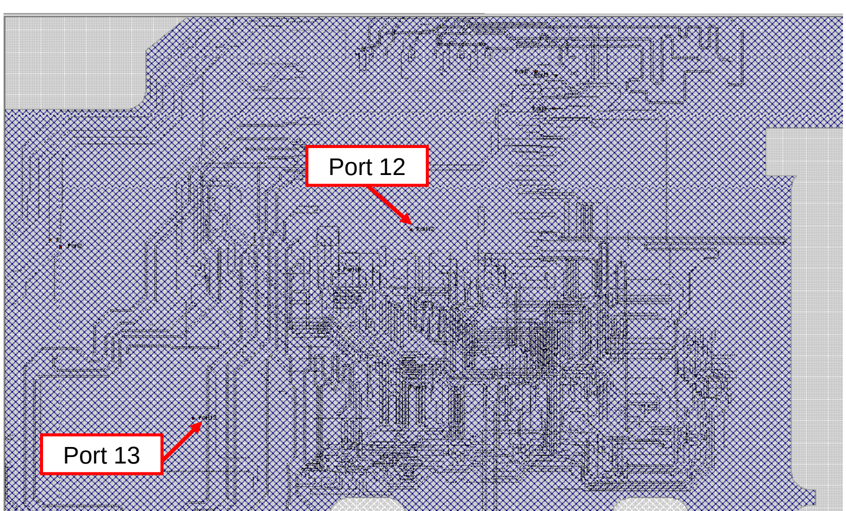
Power ports: L2 (Ref: L5) ports 12,13



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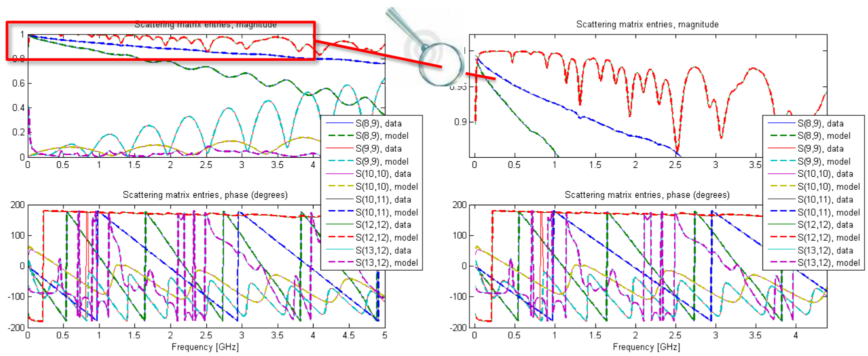
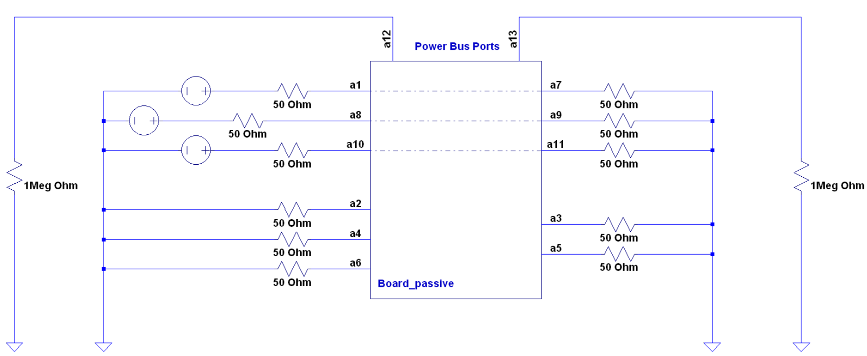
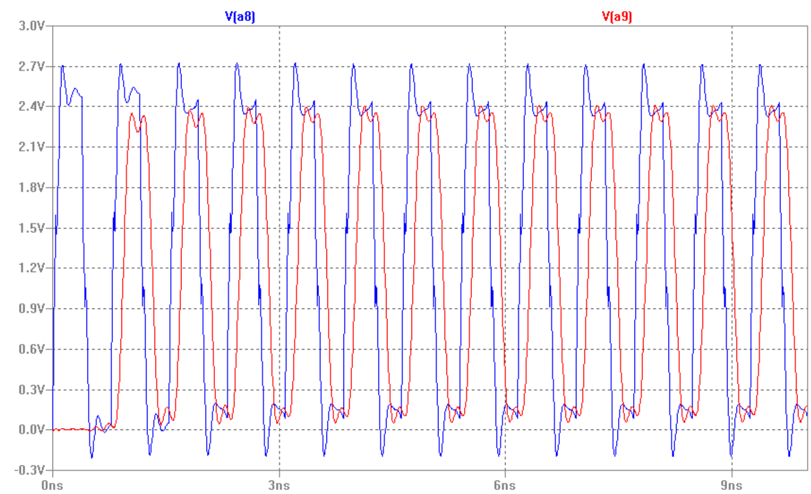
Macromodel vs S-parameters



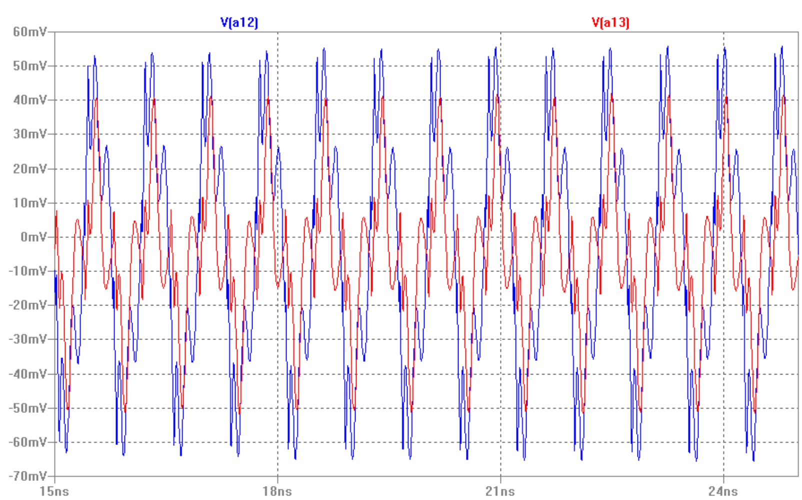
SPICE: excitation on signal lines



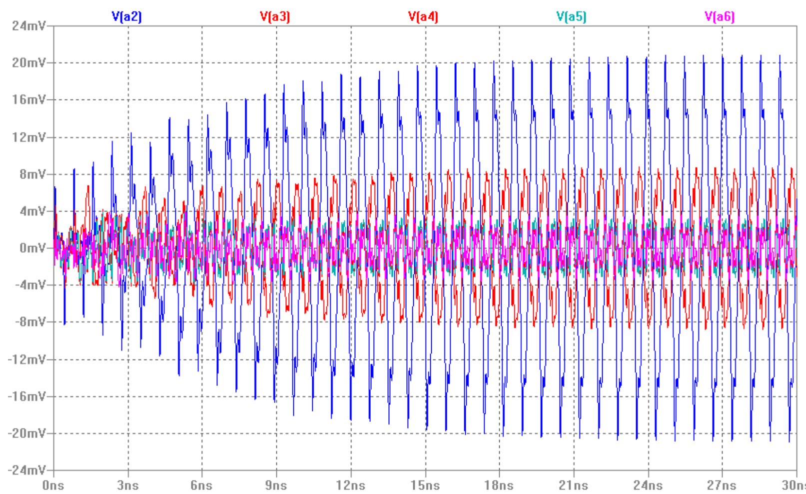
Response on a signal line, 1.3GHz



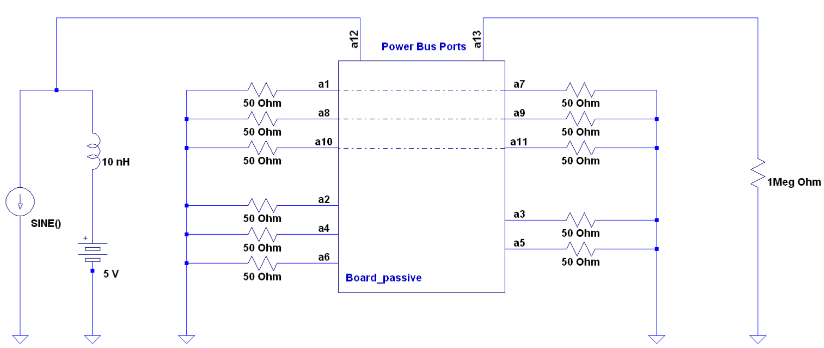
Coupling to power ports, 1.3GHz



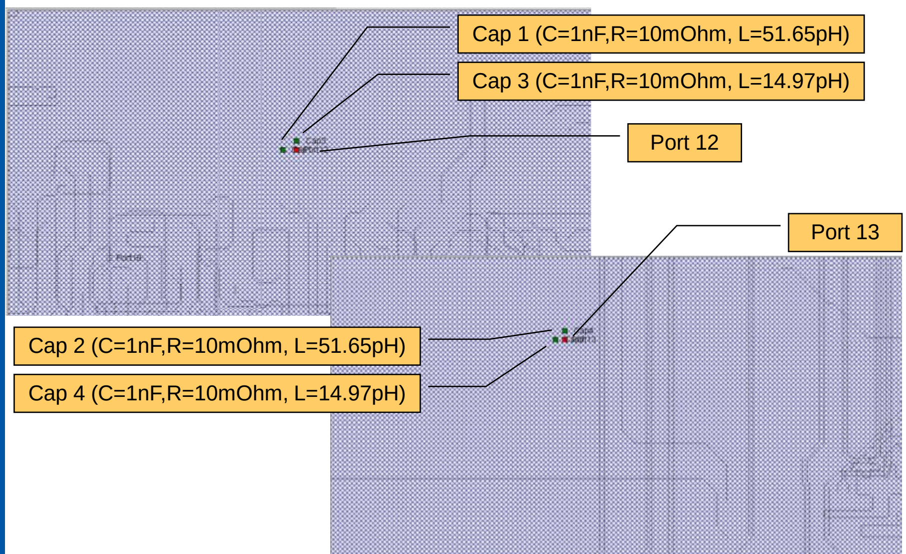
Xtalk and substrate coupling, 1.3GHz



SPICE: excitation on PDN (core switching)

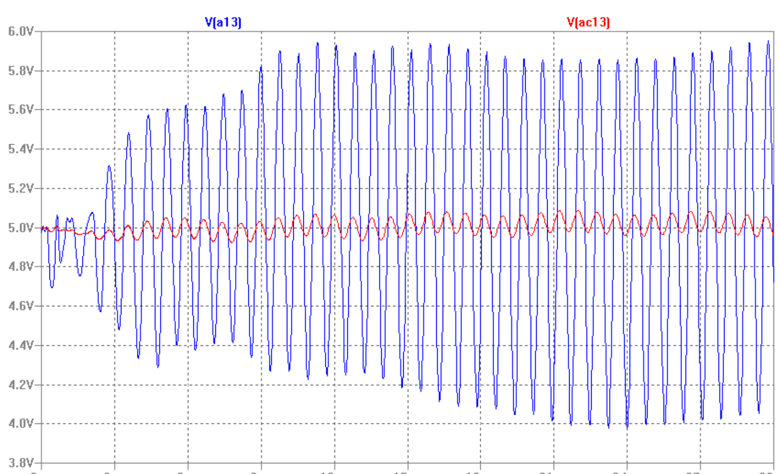


Decoupling capacitors

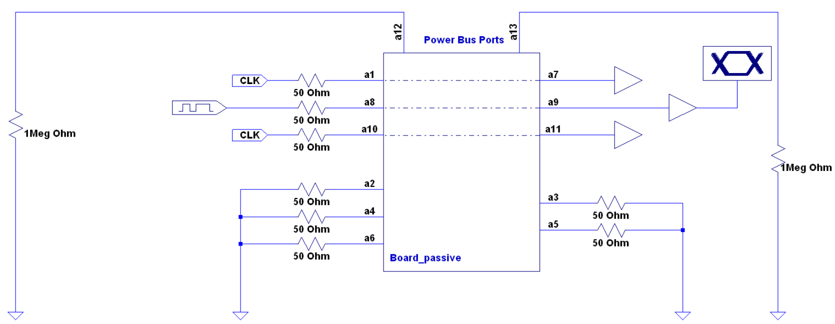


PDN response

Port 13: With and Without Caps



Eye diagram simulation: setup



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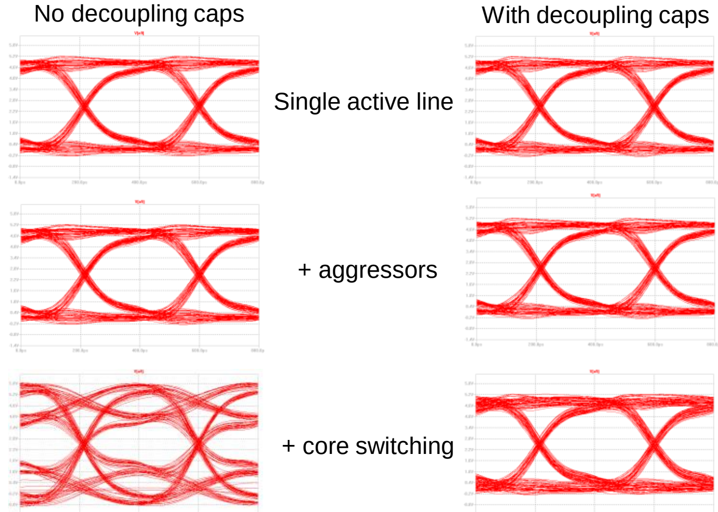
Eye diagram results, 2.6 Gb/s

No decoupling caps

With decoupling caps



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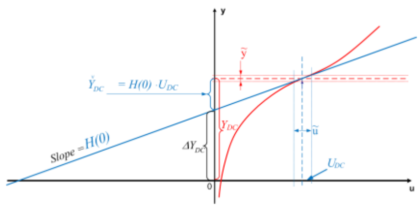
Outline

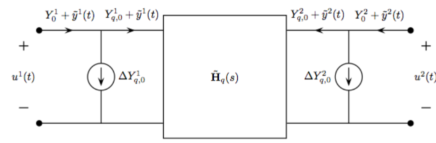
- Simulation of terminated interconnects
- Transient analysis
- Black-box passive macromodeling
- An application example
- Current work and future developments
  - Macromodeling for RF and AMS systems
  - Small-signal (parameterized) reduced-order modeling
  - Noise-compliant synthesis
- Conclusions

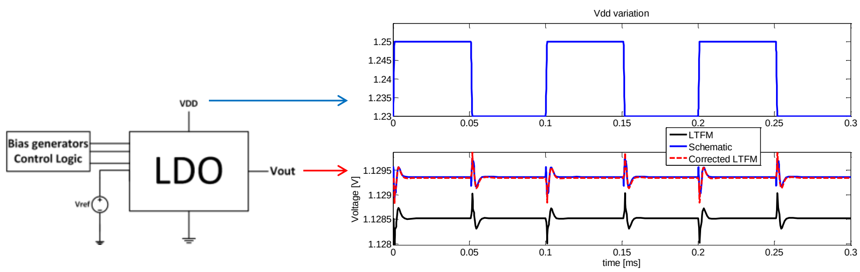
Small-signal reduced-order macromodeling

- Pre-tapeout Signal and Power Integrity verification
  - Strongly required but time consuming due to complexity
  - Devices and Circuit Blocks (CB) are nonlinear
- Local linearity assumption
  - Many components in AMS and RF transceivers are designed to operate nearly linearly under proper biasing conditions
- Behavioral Models can replace large device-level CB
  - Must preserve critical parasitic interference effects
  - Must enable fast Spice simulations also for complex designs
  - Must be numerically stable, robust and efficient
  - Must reproduce correct DC biasing conditions

Linearized macromodels and DC correction







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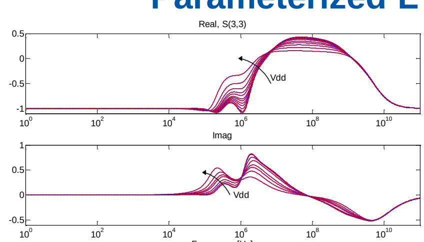
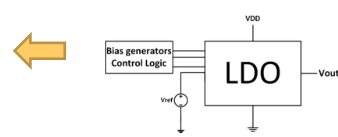
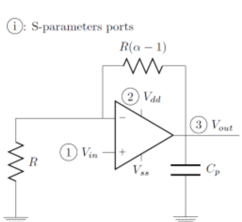
Parameterized LTFM models

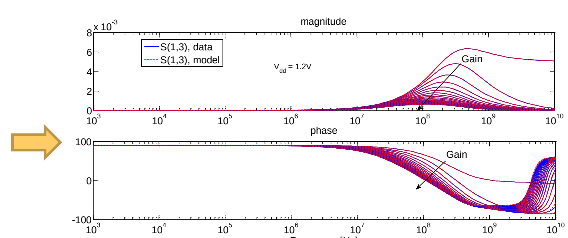


$$V_{dd} \in [0.8, 1.2]V$$

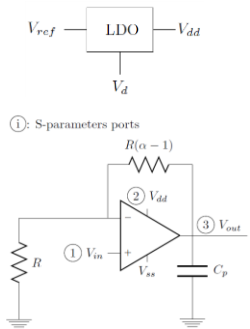


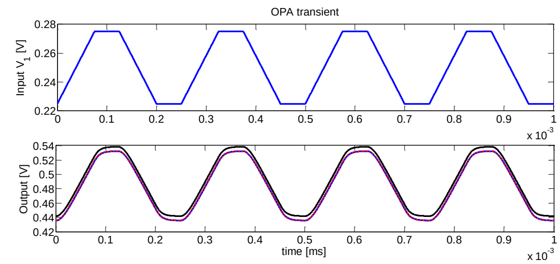
$$\mathbf{H}(s,\lambda) = \mathbf{C}(\lambda)(s\mathbf{I} - \mathbf{A}(\lambda))^{-1}\mathbf{B}(\lambda) + \mathbf{D}(\lambda)$$

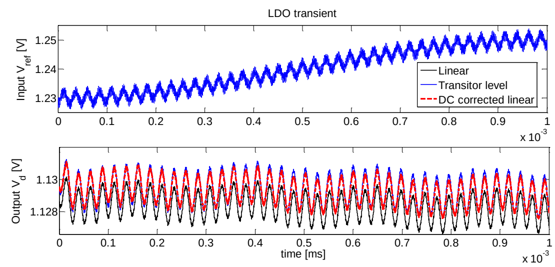




Real test case



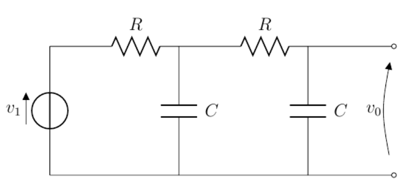




Multitone disturbance on LDO’s Vdd:
200 us transient analysis
Transitor level -> ~ 10 h
LTFM model -> ~ 8 min

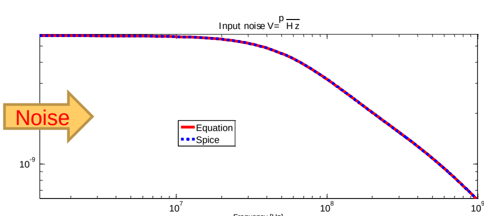
Noise from circuits

RC interconnect example



$$\bar{V}_o^2(\omega) = 4K_bT\mathbb{R}\text{e}\{Z_{out}(\omega)\}$$

Noise



Model

$$\begin{cases} \dot{\boldsymbol{x}} &= \mathbf{A}\boldsymbol{x} + \boldsymbol{b}i \\ v_o &= \boldsymbol{c}\boldsymbol{x} \end{cases}$$

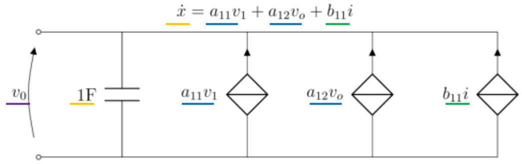
$$Z(s) = \boldsymbol{d} + \mathbf{c}(s\mathbf{I} - \mathbf{A})^{-1}\boldsymbol{b}$$

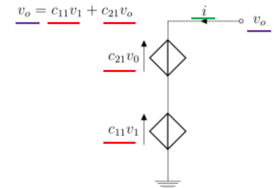
$$\mathbb{R}\text{e}\{Z_{out}(s)\} = R\frac{2-(RCs)^2}{[1+(RCs)^2]^2-(3RCs)^2}$$

$$Z(s) = \frac{R\rho_1}{sCR - p_1} + \frac{R\rho_2}{sCR - p_2}$$

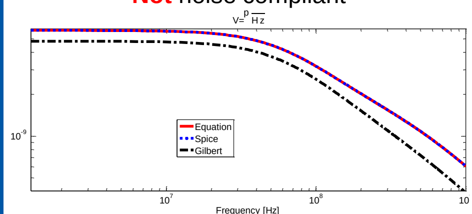
Noise compliant synthesis

$$\begin{cases} \dot{\boldsymbol{x}} &= \mathbf{A}\boldsymbol{x} + \boldsymbol{b}i \\ v_o &= \boldsymbol{c}\boldsymbol{x} \end{cases} \qquad \boldsymbol{x} = \begin{pmatrix} v_1 \\ v_o \end{pmatrix}$$

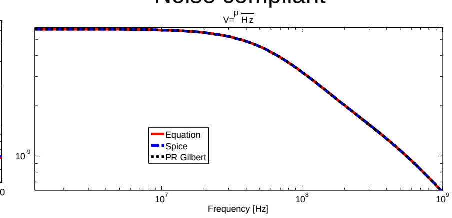




Not noise compliant



Noise compliant



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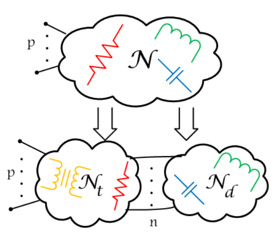
General noise compliant RLCT synthesis

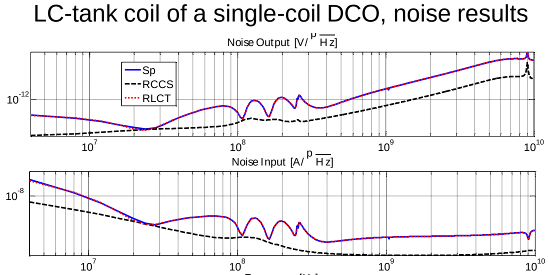


4 different RLCT “classical” synthesis methods

DC INPUT NOISE SPECTRAL DENSITY $[A/\sqrt{Hz}]$ AND OUTPUT NOISE SPECTRAL DENSITY $[V/\sqrt{Hz}]$ FOR AN RF SINGLE COIL DIGITALLY CONTROLLED TRANSFORMER.

Port		SP data		RLCT synth		RCCS synth	
In	Out	Input	Output	Input	Output	Input	Output
1	1	4.7e-8	3.6e-13	4.7e-8	3.6e-13	1.1e-8	7.7e-14
1	2	4.8e-8	3.4e-13	4.8e-8	3.4e-13	1.1e-8	7.7e-14
2	1	4.8e-8	3.4e-13	4.8e-8	3.4e-13	1.1e-8	7.7e-14
2	2	1.1e-7	1.4e-13	1.1e-7	1.4e-13	1.1e-8	7.7e-14

LC-tank coil of a single-coil DCO, noise results



Synthesis’ complexity:

Noise compliant:

$O(n^2p^2)$ ☹

Not noise compliant:

$O(np^2)$ ☺

n: model order

p: number of ports

Conclusions

- Application example shows
  - Need for coupled Signal/Power Integrity analysis
  - Need for transient analysis
  - Need for accurate and efficient Signal/Power models
- Macromodeling
  - Provides excellent solution for model extraction
  - Computes compact models from
    - Direct measurements
    - Time or frequency domain full-wave simulation results
    - Based on rational approximation of system transfer functions
    - Requires passivity verification and enforcement
    - Requires "good" data to start with
  - Enables fast transient system-level simulation